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Hydrogeochemistry of pre-Mississippian brines, Williston Basin, Canada–USA

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Abstract

Spatial variations of solute chemistry in basinal brines have been used to determine the origin of formation waters and to infer regional patterns of fluid flow and dominant diagenetic processes active in the Williston Basin, Canada–U.S.A. Preliminary results of a regional, 200 well sampling program in pre-Mississippian formations, show that these brines involve three chemically distinct waters. A $CaSO_4$ brine (TDS $< 30{,}000$ mg/l) exists along the southwest and east flanks coinciding with meteoric input. A Na–Ca–Cl brine (TDS $> 300{,}000$ mg/l) is located in the deepest part of the basin, while a Na–Cl brine is found in the remaining volume. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

Regional fluid flow in deep aquifers plays an important role in large-scale geological processes within cratonic sedimentary basins, including diagenesis, hydrocarbon migration and ore deposit formation (Bethke and Marshak, 1990; Garven, 1995). Awareness of relationships among regional groundwater flow, rock–water interaction and solute transport can aid in the understanding of the past and present patterns of water movement in the rock framework (Tóth, 1984). Spatial variations in chemical composition can be used to document fluid migration trajectories and even estimate the degree of hydraulic continuity in a basin (Hanor, 1994). These types of studies have been used to obtain a more accurate description of fluid flow in many cratonic basins e.g. (Hitchon and Friedman, 1969; Carpenter, 1978; Connolly et al., 1990; Stueber et al., 1998) and others.

Solute chemistry analysis has been completed in the Williston Basin, Canada–U.S.A., to some degree as well; however, most individual studies of the Williston Basin have been limited by political boundaries (Benn and Rostron, 1998). Existing regional compilations are mainly derived from Drill Stem Test (DST) samples. Hydrocarbon production in pre-Mississippian formations in the Williston Basin has provided the opportunity to sample formation waters and obtain new data that yields more information about deep basin hydrogeology. Characterizing fluid flow may aid in the understanding of hydrocarbon entrapment and mineral deposition, potentially identifying new deposit locations (Collins, 1975; Tóth, 1984).

2. Study area

Structurally, the Williston Basin is a wide, indistinctly bounded, shallow depression centered in northwestern North Dakota and extending radially outward into regions of Saskatchewan, Manitoba, South

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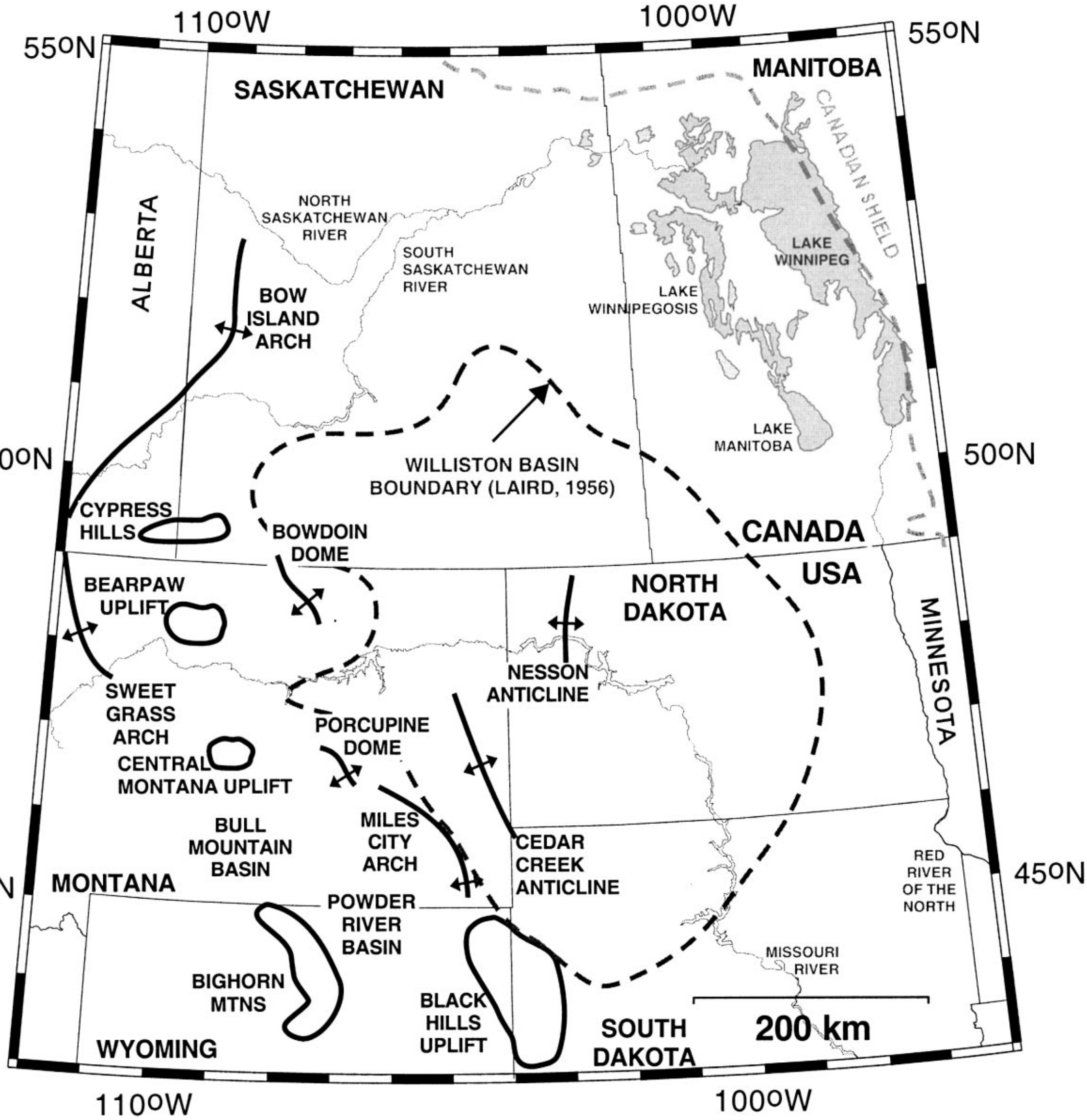

Fig. 1. Approximate regional extent of the Williston Basin, Canada–USA represented by dashed line (based on Laird and Folsom, 1956).

Dakota and Montana (Fig. 1). This roughly circular intracratonic sedimentary basin covers approximately 518,000 km^2 (Fuller, 1961). Subsidence during Late Cambrian or Ordovician time initiated active deposition within the basin that persisted until the Mesozoic (Peterson and MacCary, 1987). In the present basin center, the pre-Mississippian rocks are covered by 5000 m of Upper Paleozoic, Mesozoic, and Tertiary deposits (Peterson and MacCary, 1987). These deposits thin to the northeast where the rocks outcrop and subcrop on the Canadian shield in Manitoba.

The pre-Mississippian strata can be subdivided into three sections: (i) a lower shale and sandstone sequence of Upper Cambrian and Middle Ordovician age; (ii) dolostones and limestones that range from Middle Ordovician to Upper Silurian in age and (iii) an overlying package of Devonian sediment (Peterson and MacCary, 1987). The Middle Devonian Prairie

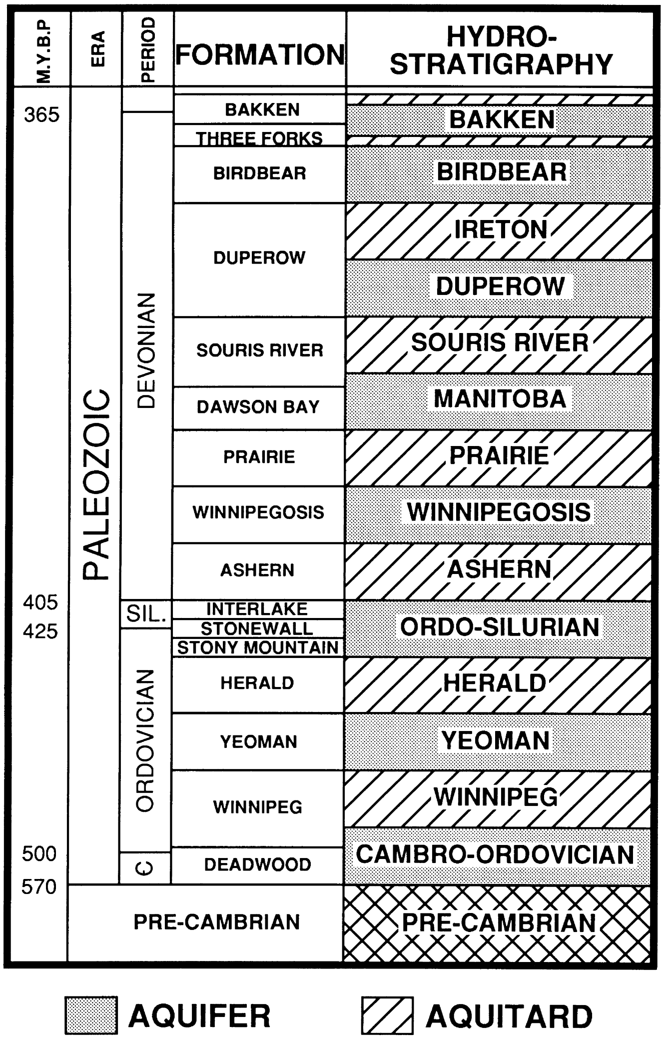

Fig. 2. Hydrostratigraphic units of the pre-Mississippian section.

Evaporite Formation is of greatest significance in a study of basin hydrogeochemistry. Deep basinal brines found within the pre-Mississippian section are often attributed to the dissolution of anhydrite, halite and dolomite found within the Prairie Evaporite Formation (Chipley and Kyser, 1991).

3. Hydrogeology

Although the geological framework of the Williston Basin is well documented, fluid movement within that framework is not (Bachu and Hitchon, 1996). Strata from Precambrian basement to the Bakken shale have been subdivided into 16 hydrostratigraphic units (Fig. 2). Aquifers are predominantly clastic or carbonate in composition and aquitards include shale, evaporites and filled breccias. Both aquifers and aquitards are locally and laterally discontinuous.

The present hydrodynamic regime in the Williston Basin is thought to have developed in response to the Laramide Orogeny (Bachu and Hitchon, 1996) on the western margin of North America. This tectonic regime caused uplifts in Montana and South Dakota

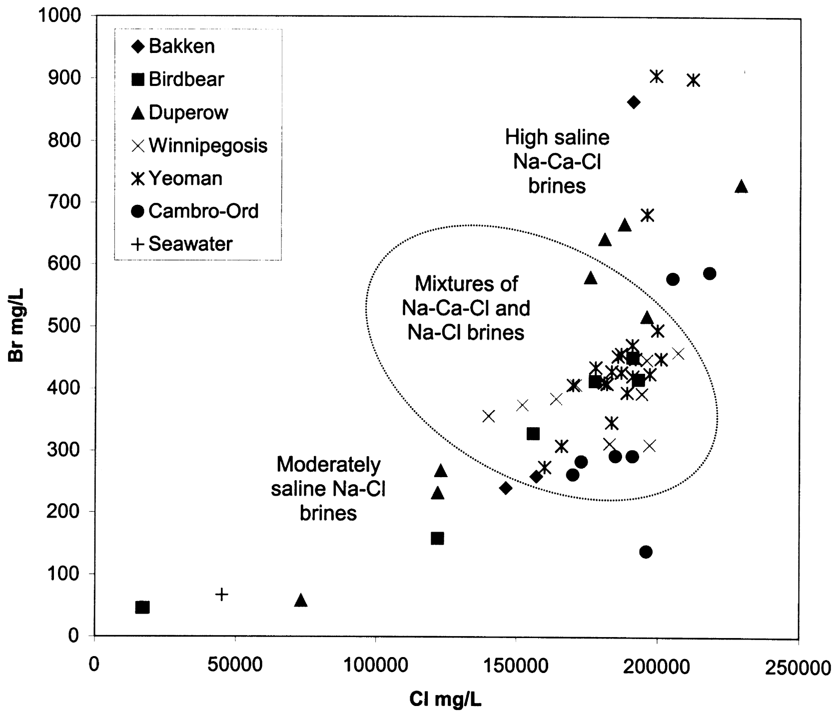

Fig. 3. Mixing of brines with different dominant chemistry.

including: the Black Hills, Pryor Mountains, Bighorn Mountains, Beartooth Mountains and Little Rocky Mountains (Fig. 1). The current gravity-driven flow model of the basin involves recharge at the uplifts, lateral flow across the basin toward the north–east and discharge along the eastern margins (Downey and Dinwiddie, 1988; Bachu and Hitchon, 1996).

4. Brine sampling results

To date, two hundred formation water samples have been collected from producing oil wells across Montana, North Dakota, South Dakota and Saskatchewan. So far 50 have been analyzed for major and minor ions, alkalinity, organic acids and stable isotopes (Rostron and Holmden, this volume) Analysis of the remaining samples is ongoing. Chemical analysis of these samples reveal brines with concentrations averaging 300,000 mg/l with some in excess of 380,000 mg/l, verifying results of DST derived hydrogeochemical studies. These waters are not homogeneous in content, but instead can be grouped into three types. The first type found in a brackish water zone entering at south-western Saskatchewan and north-eastern Montana is predominantly $Ca–SO_4$, with TDS $< 30,000$ mg/l. The second, a Na–Cl type with TDS ranging from 100,000–200,000 mg/l, is situated in the northern part of the basin. The third type of brine comprised of Na–Ca–Cl waters has TDS $> 300,000$ mg/l and anomalously low sulphate concentrations. It is located in the basin center.

5. Discussion

Since relative distributions and concentrations of solutes denote the degree of activity of the flow system (Tóth, 1984; Stueber et al., 1998), these three types of waters provide an indication of the kind of flow regimes present in the Williston Basin. The brackish water area is the most active flow system. The Na–Cl formation water type shows water somewhat evolved but still fairly active in comparison to ancient Na–Ca–Cl type formation water that is highly evolved (Collins, 1975). Although

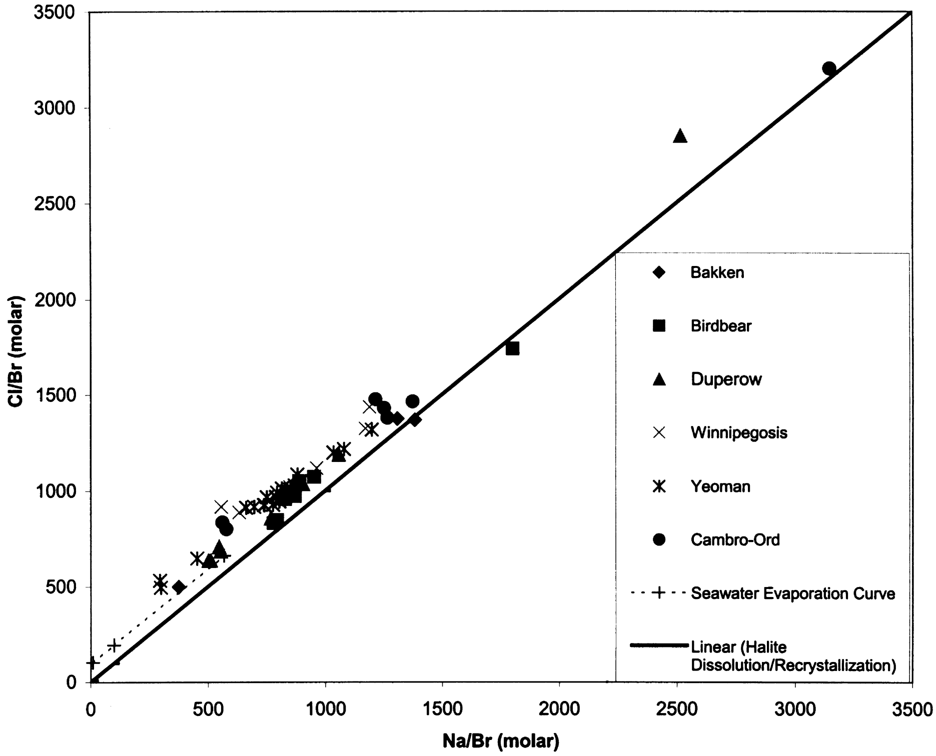

Fig. 4. Cl/Br vs. Na/Br molar ratios for pre-Mississippian brines relative to the compositional trend formed by seawater (SW = seawater composition).

flow systems relating to the two higher TDS zones might be less active, particularly in the Na–Ca–Cl brine location, there is some overlap in solute compositions in the pre-Mississippian formations (Fig. 3). Mixing of Na–Cl and Na–Ca–Cl water, and thus deep basin flow is evidenced by this overlap, although the curvature in the data reflects another process controlling brine composition in addition to simple two endmember mixing (Hanor, 1987).

In addition to different zones of waters present in the Williston Basin, there may also be different sources of solutes. Saline formation waters can originate from dissolution of halite and/or the infiltration of subaerially evaporated seawater (Hanor, 1987; Land et al., 1988). It is generally accepted that halite dissolution is the source of the high salinities in the pre-Mississippian section of the basin (Chipley and Kyser, 1991), although a smaller scale study has also pointed to subaerial evaporation of seawater as a source of salinity (Wittrup and Kyser, 1990). Na–Cl–Br systematics have been applied to this latest data set in order to distinguish between these different solute sources, documenting the true cause of the salinity on a regional scale. Molar ratios of Cl/Br vs. Na/Br for some samples plot below the value for seawater, indicating that residual evaporated seawater is indeed left in the basin (Fig. 4).

Moreover, brines that evolved wholly or partly from subaerial evaporation of seawater are not restricted to one aquifer. They are found both above and below the Prairie aquitard i.e. beyond the formations immediately in contact with halite. This indicates vertical mixing of residual evaporitic brines and brines derived from halite dissolution (Fig. 4). Additionally, there is no distinct lateral boundary between the two types of solute sources (Fig. 5). Preliminary data suggest the highest salinity waters in the basin are derived from a mixture of remnant brines (from evaporated seawater) and brines due to halite dissolution. The presence of percentages of

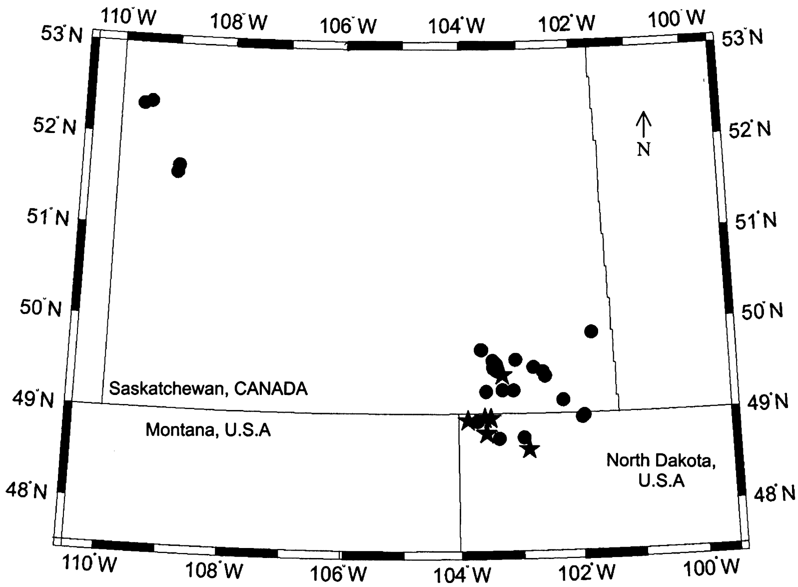

Fig. 5. Relative spatial distribution of pre-Mississippian brines evolved exclusively from halite dissolution (represented by circles) and mixtures of subaerially evaporated seawater and brines evolved from halite dissolution (represented by stars), $n = 50$ samples.

subaerially evaporated brine in the basin center appears to be correlated with the Na–Ca–Cl type waters also found there.

6. Conclusions

New wellhead-derived hydrochemical data shows mixing between two endmembers: ancient evaporated seawater and halite dissolution. This conflicts with the current model that dissolution of the Prairie Evaporite Formation alone accounts for the observed high salinites within the Williston Basin. Vertical mixing of these two components ensures that brines formed through halite dissolution are not just present where water is in contact with halite. Furthermore, mixing both above and below the Prairie Evaporite suggests that either the flow system responsible for the mixing is not strongly affected by the aquitards, or that the lateral discontinuity is great enough so vertical flow is not inhibited and is more or less consistent over the whole pre-Mississipian sequence. The spatial co-existence of residual evaporated seawater along with halite-sourced brines confirms there is lateral flow and thus mixing along regional flow paths as well. This is further supported by overlap in solute compositions for the two more saline water types, which border one another laterally. More analysis of this data set is necessary to identify the most active flow systems, extent of recharge penetration, and dominance of lateral vs. vertical flow in the Williston Basin.

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